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14. ABSTRACT
Electromechanica, Inc. designed, fabricated and evaluated a proof of concept robotic tool for in situ inspection and remediation of fleet piping. The robotic tool is based on pneumatically actuated peristaltic motion. This in-pipe motion is accomplished by the use of inflatable pneumatic annular grippers in concert with a novel flexible pneumatic linear actuator capable. This linear actuator is capable of actuation while bent to conform to the contours of a piping system. The flexible linear actuator allows the robot to move through bends that would otherwise be inaccessible with conventional rigid actuators. The robot was designed and demonstrated to negotiate a nominal 3 in. (76 mm) ID pipe.

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I. Abstract

Electromechanica, Inc. designed, fabricated and evaluated a proof of concept robotic tool for *in situ* inspection and remediation of fleet piping. The robotic tool is based on pneumatically actuated peristaltic motion. This in-pipe motion is accomplished by the use of inflatable pneumatic annular grippers in concert with a novel flexible pneumatic linear actuator capable. This linear actuator is capable of actuation while bent to conform to the contours of a piping system. The flexible linear actuator allows the robot to move through bends that would otherwise be inaccessible with conventional rigid actuators. The robot was designed and demonstrated to negotiate a nominal 3 in. (76 mm) ID pipe including horizontal and vertical runs with bends representative of small diameter piping common to Naval ships.

Robot control is accomplished by an embedded Linux system-on-module computer integrated into the robot. The robot's computer communicates via TCP/IP to an operator control station (OCS) for operator interface to the system. Power, control commands and video are transmitted between the robot and OCS using a power over Ethernet (PoE) tether. The tether also includes the air supply for the robot and serves as a failsafe retrieval method.

The prototype robot included a high definition IP video camera, environmental pressure sensor (for future depth sensing) and roll/pitch sensors in the camera and control modules. Camera orientation sensors were used to dynamically correct video orientation to maintain a horizontal reference. Additional sensors provided remote health monitoring of the robot including pneumatic bus pressure, electronics temperature and all bus voltages.

Electromechanica, Inc. has applied for a provisional patent for the flexible linear actuator designed as part of this R&D contract.

II. Introduction

Fleet piping systems are complex, space constrained systems which are difficult to inspect using standard external inspection techniques. Pipe lagging, bulkhead penetrations and tightly packed equipment makes external access prohibitively expensive and difficult; see Figure 1 and Figure 2.

Figure 1 - Complex, space constrained fleet piping

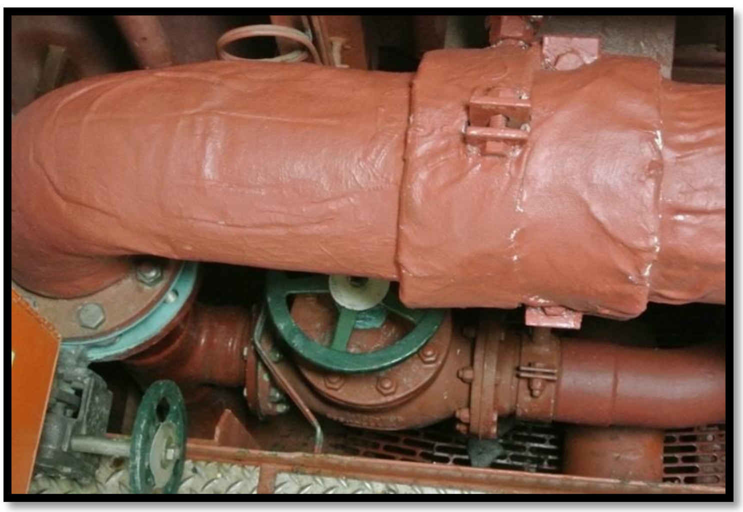

Figure 2 - Pipe Lagging

To facilitate inspection it was desired that a means of internal inspection be researched and developed. Electromechanica Inc. has been tasked with developing a robotic tool which may deliver a sensor package capable of real-time corrosion/erosion and pipe wall measurements. This robotic system will also allow tools to be deployed for *in situ* remediation. Implementation of this system will allow for fleet preventative maintenance (PM), ensuring that possible failures are detected and remediated before they result in failures that adversely impact fleet operations.

III. Discussion

A. Overview

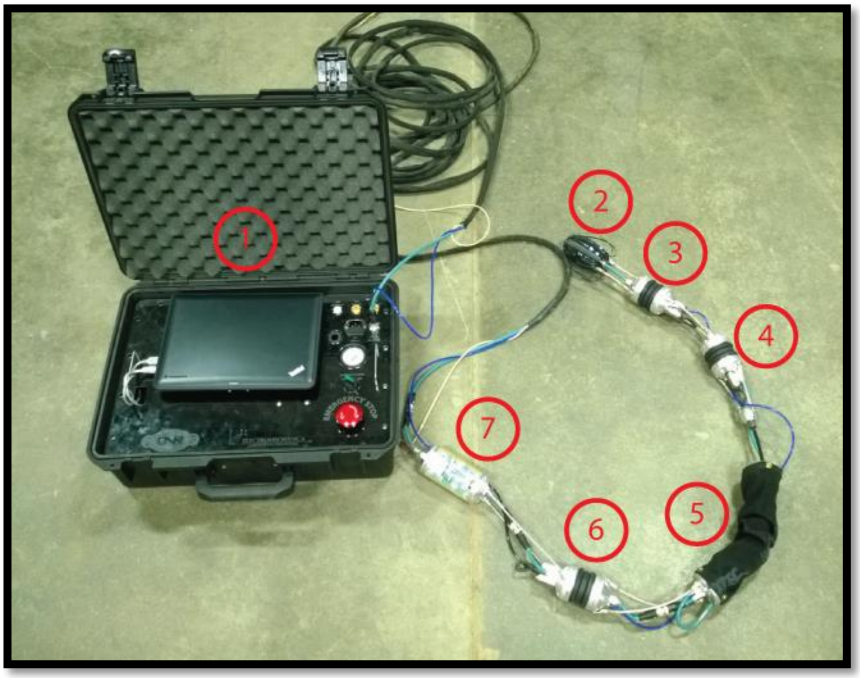

Figure 3 - Robotic inspection system

Electromechanica, Inc. has designed and built a robotic system for internal pipe inspection. This proof of concept was designed with a target internal pipe diameter of 3”. 3” I.D. piping was selected as it is a representative average of fleet piping. The system has been designed with modularity and scalability in mind for future capabilities. The system can be seen in Figure 3, with callouts below:

1. Operator Control Station
2. Front Camera Housing
3. Front Gripper
4. Front Gripper #2
5. Flexible Pneumatic Cylinder
6. Rear Gripper
7. Electronics Enclosure

System locomotion is accomplished by a pneumatically actuated peristaltic motion. This motion is generated by synchronized actuation of inflatable grippers and a flexible pneumatic cylinder as shown in Figure 4.

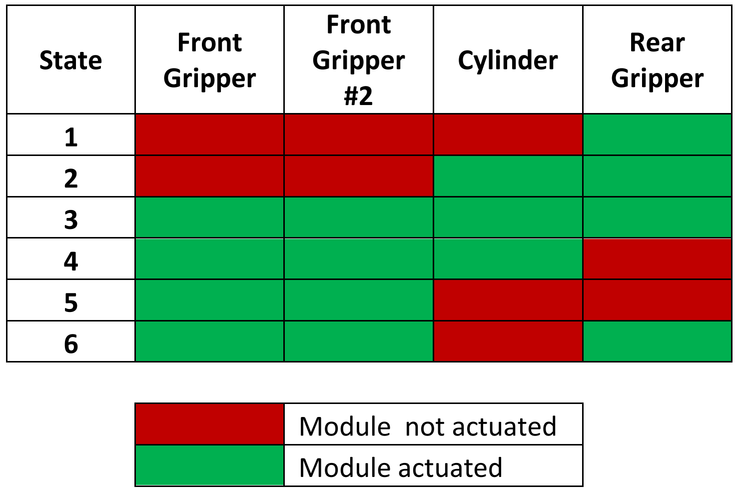

Figure 4 - Robot motion states

The flexible pneumatic cylinder provides the linear motion of the system. It is capable of extending approximately 5.5 inches (140mm) per stroke. The key feature of the flexible pneumatic cylinder is its flexible nature. This feature allows it to easily bend around the various geometries typically found in pipe systems, while maintaining its full stroke length.

The grippers of the system are designed around an inflatable seal, which inflates radially as air is applied to the gripper. The seals are toroid shaped, providing full 360° grip to the pipe I.D. during actuation. The system makes use of three grippers, two ahead of the cylinder and one behind. This topology was selected in order to maximize gripping force while the robot was pulling its tether, which at long distances will become significant due to its weight and frictional forces developed between it and the pipe interior.

B. Electrical

1. Controller

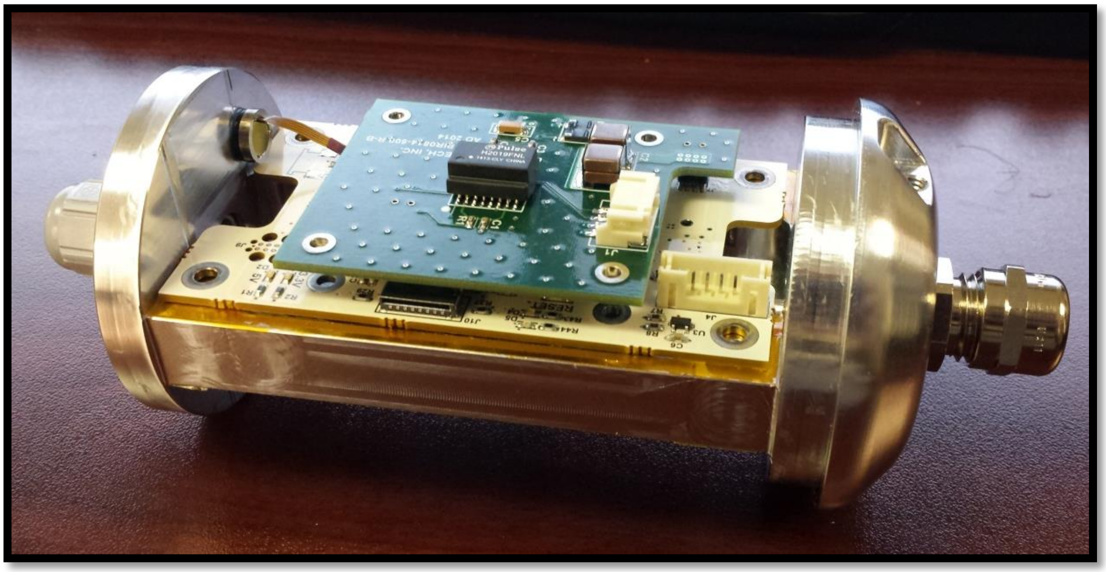

Figure 5 - Robot Controller

An embedded Linux computing platform was implemented for robot control. This solution provides a scalable solution for future iterations of the robot which may require additional hardware and software requirements that have not been implemented or thought of during this phase of the project.

Figure 6 - Controller, showing Linux SoM

To design a reliable system, it was decided that a System on Module (SoM) would be used instead of designing an embedded computing system from scratch. The SoM is a single integrated module which contains the processor, RAM, power management, and flash memory. The SoM provides access to peripherals via two large connectors on the bottom, as shown in Figure 7. This approach allows for a much faster development time, eliminating the risks involved in high speed memory design.

Figure 7 - PHYTEC AM335x SoM Bottom Side

The PHYTEC AM335x SoM was selected due to its small size, and peripheral capability. The SoM measures 50mm x 44mm. The SoM processor is an ARM Cortex-A8 running at720MHz with 512MB of ram, and 512MB of flash memory. Peripheral capability includes 2 Ethernet ports, SD/MMC, Dual USB 2.0 OTG, CAN, UART, SPI and I2C.

To interface the SoM to the robot three interface PCB’s were built. These are the Interface PCB, Power PCB and Ethernet PCB. These PCB’s are used to interface the SoM to the robot.

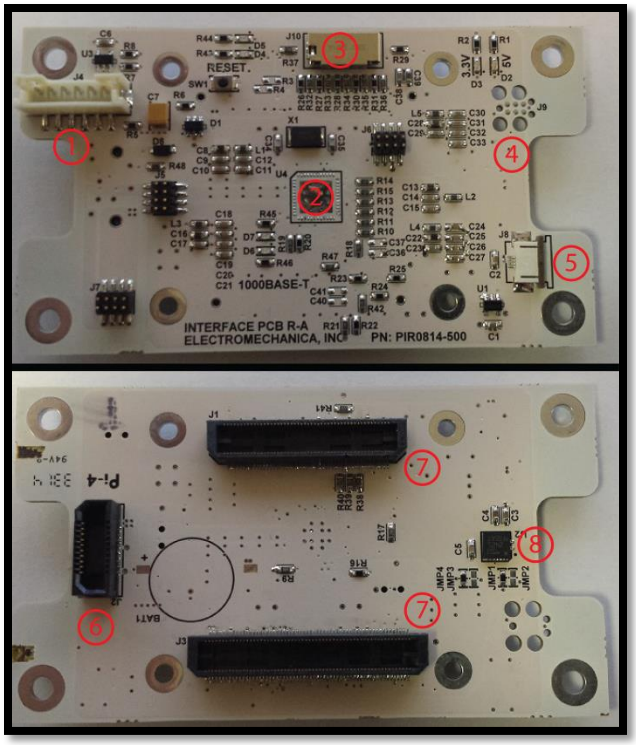

Figure 8 - Interface PCB top and bottom

Direct connection to the SoM is accomplished by the Interface PCB, shown in Figure 8. This PCB allows for the breakout of the many functions of the SoM required for the robot build. Some of the PCB features are numbered in red text, these are:

1. USB2.0 OTG
    a. USB capability for future rear camera capability.
2. 1000base-T Ethernet PHY
    a. Future Ethernet bridging capability for reduced tether size.
3. SD/MMC
    a. Used for firmware updates and data retrieval. Not used in operation.
4. UART Connection
    a. Used for robot debugging and firmware updates.
5. Pressure sensor connection
    a. Used to measure local ambient pressure.
6. Connection to Power PCB
7. SoM connections
8. 9-DoF IMU
    a. Inertial measurement unit for robot spatial awareness.

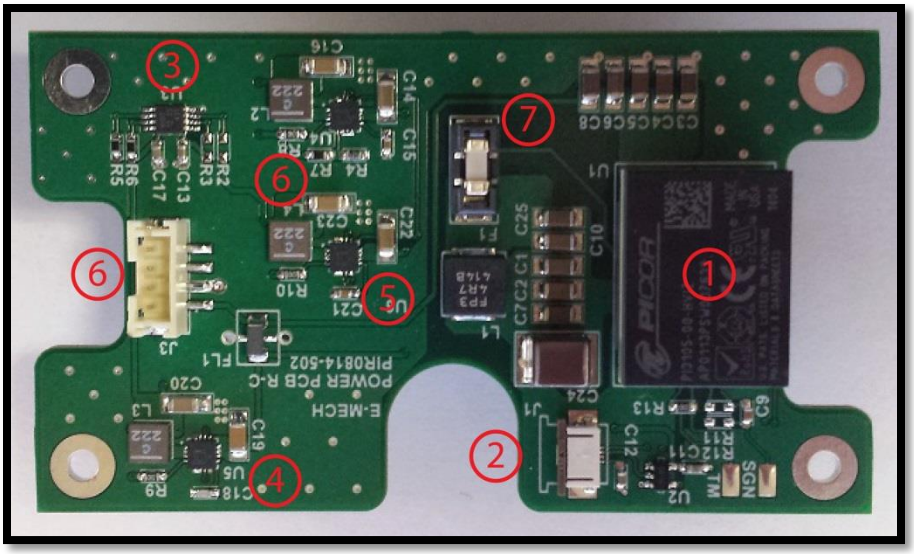

Figure 9 - Power PCB

The Power PCB (Figure 9) is responsible for generating the various voltages and currents required by the SoM and robot. This PCB accepts the incoming 48VDC from the tether and generates the required 12V, 5V, 3.3V and 1.2V at their required currents. PCB features include:

1. 12V DC-DC converter
    a. Wide input range DC-DC converter (36V-75V) generates 12V output at 60W.
2. Pressure sensor connection
    a. Used to measure supply bus pressure.
3. I2C buffer/line driver
    a. Translates 5V I2C to 3.3V for the SoM and allows for the driving of longer buses with high capacitance.
4. 5V DC-DC converter
    a. 5V used for SoM power and I2C bus power.
5. 3.3V DC-DC converter
    a. 3.3V used for pressure sensors and 1000base-T transceiver.
6. 1.2V DC-DC converter
    a. 1.2V used for 1000base-T Ethernet transceiver.
7. Fuse for 12V converter protection.

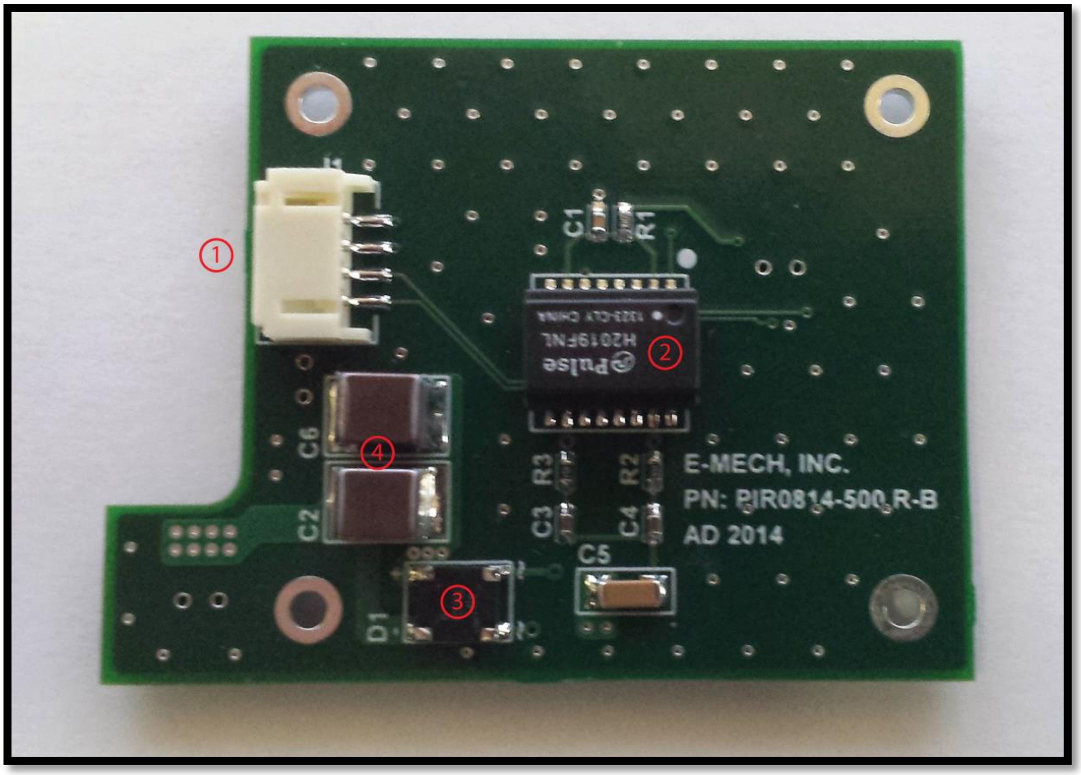

Figure 10 - Ethernet PCB

The Ethernet PCB (Figure 10) is responsible for routing the incoming Ethernet and Power over Ethernet (PoE) signals to the Interface and Power PCB's. This PCB's features include:

1. Tether connection
    a. 100base-T Ethernet and Power over Ethernet connection.
2. Ethernet transformer
3. Bridge rectifier
    a. Used for polarity protection.
4. Lump capacitance
    a. 44uF of local energy storage for transient events.

2. Gripper Electronics

Figure 11 - Pneumatic Gripper

As previously mentioned, the system makes use of multiple pneumatic grippers to aid in traction. The grippers present a unique challenge from an electronics stand point. They require intelligent control, pressure monitoring and slave control via an I2C bus while being contained in a very small form factor. To solve this issue, gripper control was split into two PCB assemblies, the top and bottom PCB's seen in Figure 12.

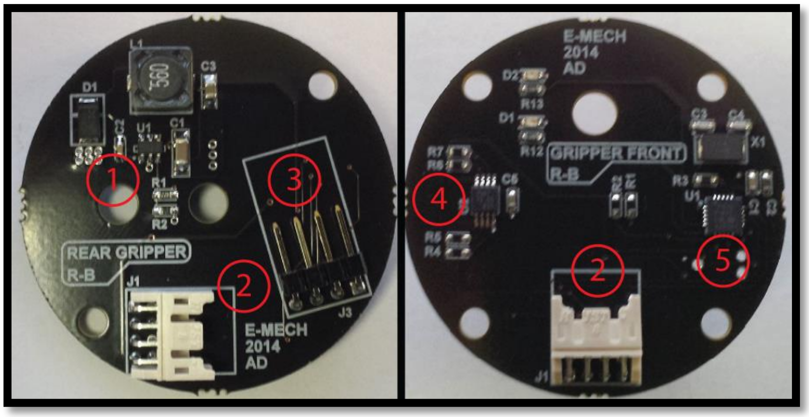

Figure 12 - Gripper top and bottom PCBs

Some of the features of this PCB include:

1. DC-DC converter
    a. Converts the system 12V supply to 5V required by the microcontroller at the gripper.
2. Bus connection
    a. Main interface for gripper connection to the system I2C and power bus.
3. Valve connections
    a. Connection interface for the two solenoid valves used in the system.
4. I2C Buffer
    a. Allows the I2C bus to be used over longer distances in cable based designs.
5. Microcontroller
    a. PIC16F1829 8 bit, 14kB flash
        i. I2C slave to robot controller.
        ii. Toggles solenoid valves to inflate and deflate seal on robot controllers command.
        iii. Measures seal pressure to stop inflating once internal pressure reaches a preset pressure.

3. Cylinder Electronics

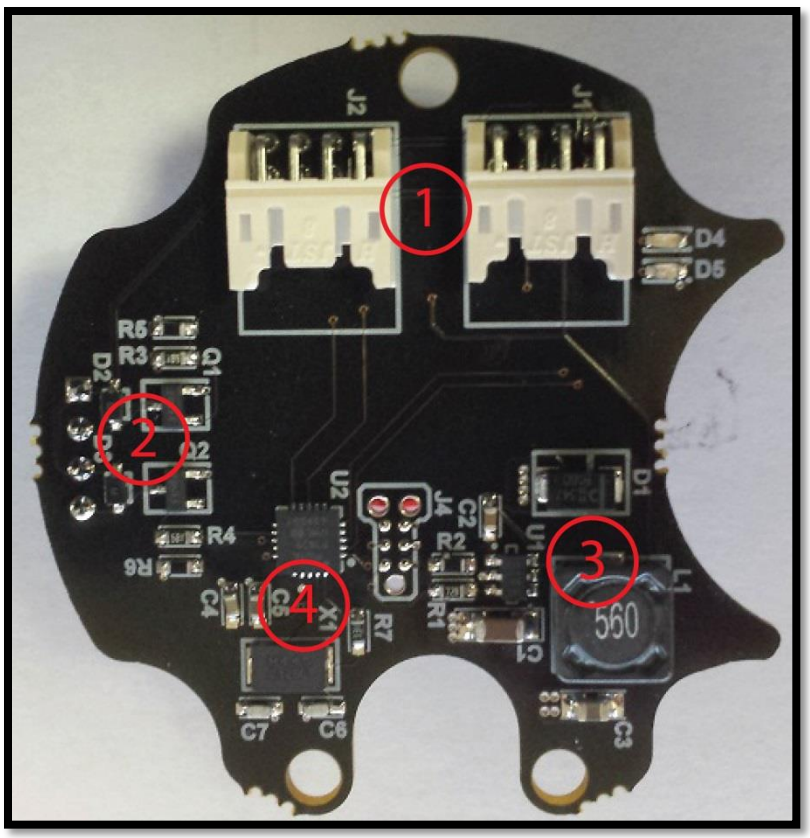

Figure 13 - Cylinder control PCB

Cylinder control is accomplished by a single PCB assembly, located in the base of the cylinder. The function of the Cylinder PCB is nearly identical to the two gripper PCBs, with the major difference being that there is no feedback from the cylinder to the controller. In the current iteration actuation of the cylinder is accomplished by delaying a preset amount of time. In future iterations it is anticipated that a feedback mechanism will be incorporated into the design, allowing the controller to know when the cylinder has reached its full stroke length.

Cylinder control PCB features include:

1. Bus Connections
    a. Main interface for gripper connection to the system I2C and power bus.
2. Valve drive circuitry
    a. Required components to actuate valves.
3. DC-DC Converter
    a. Converts the system 12V supply to 5V required by the microcontroller at the cylinder.
4. Microcontroller
    a. PIC16F1829 8 bit, 14kB flash
        i. I2C slave to robot controller.
        ii. Toggles solenoid valves to extend and retract the cylinder on robot controllers command.

4. Camera Housing Electronics

Figure 14 - Camera and associated PCBs

The camera housing contains all the necessary components to provide the operator with a real time view of the pipe interior for inspection. The system makes use of a high resolution (1280 x 1024) Ethernet camera with a wide angle lens (5mm FL, f/2.5) to provide the highest possible quality image to the operator. Three PCB's are used in the housing, these are the camera interface PCB, camera daughter PCB and the LED PCB.

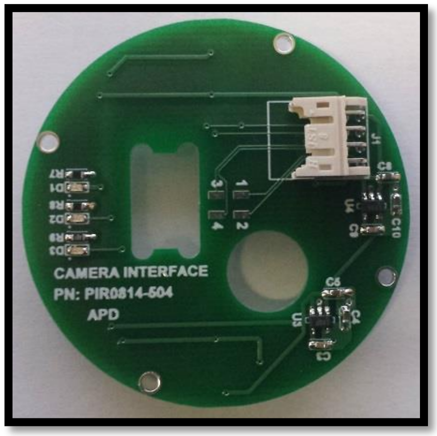

Figure 15 - Camera interface PCB

The camera interface PCB is used for interface to the camera and for generation of the required voltages for the I2C bus, accelerometer and LED driver on the daughter PCB. A unique low profile connection method was implemented to connect the camera to the PCB, see Figure 20. This method was desired as it allows for robust camera connection while adding effectively zero length to the housing.

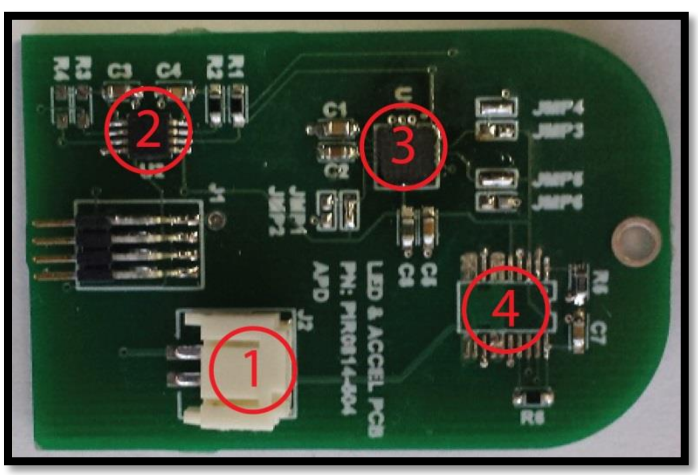

Figure 16 - Camera daughter PCB

The camera daughter PCB (Figure 16) allows for a 9-DoF inertial measurement unit (IMU), and an LED driver to be accessed and controlled by the robot controller. Data from the IMU is used for spatial awareness, and for image orientation as described in the software section. The LED driver, while not currently used, will allow for real time dimming of the LED ring. This will allow the user to dim the LED's to achieve the best possible picture quality.

The camera daughter PCB includes:

1. Connection to LED PCB
2. I2C Buffer
    a. Allows the I2C bus to be used over longer distances in cable based designs.
3. IMU, 9-DoF
4. LED Driver
    a. Not used in current design due to I2C conflicts. Future iterations may include LED dimming.

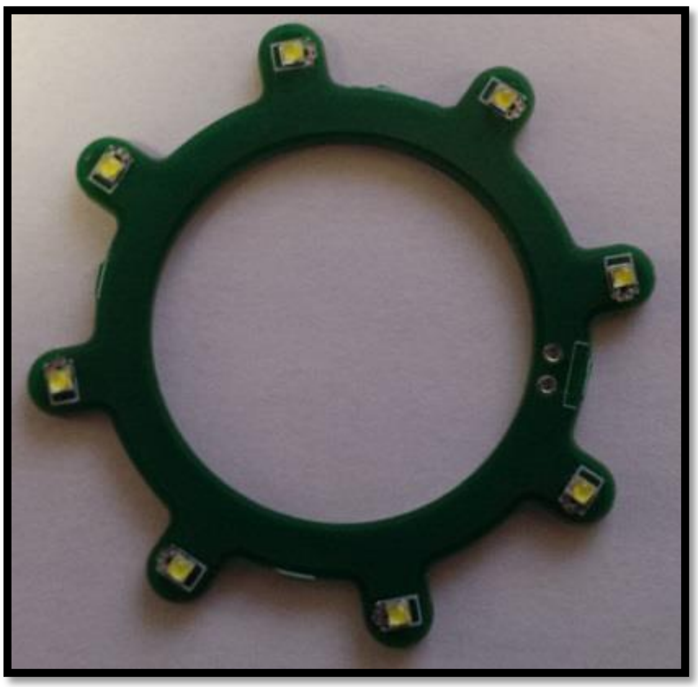

Figure 17 - Camera LED PCB

The camera LED PCB (Figure 17) is used for internal pipe illumination. The PCB contains eight (8) high intensity miniature bright white LED's. Each LED is capable of 252lm providing a total luminous flux of 2016lm for pipe illumination. The completed housing with LED's illuminated can be seen in Figure 18.

Figure 18 - Camera housing in pipe with LED's illuminated

5. Operator Control Station

Figure 19 - Operator control station

An operator control station (OCS) has been designed and built, see Figure 19. This control station makes use of a Lenovo ThinkPad laptop for graphical interface to the operator, and general control of the robotic system.

The OCS includes an air filter and pressure regulator to ensure that the incoming air is clean and at the correct pressure for use in the robot. Air pressure is interlocked to the electrical system by a solenoid

valve. E-Stop actuation simultaneously removes all energy sources from the system, electrical and pneumatic.

The OCS also serves as the power source for the robotic system. The OCS is designed to accept a 120VAC input, which is used to derive the 48VDC required to power the robot. E-Stop actuation will remove both the 120VAC and 48VDC sources from the system.

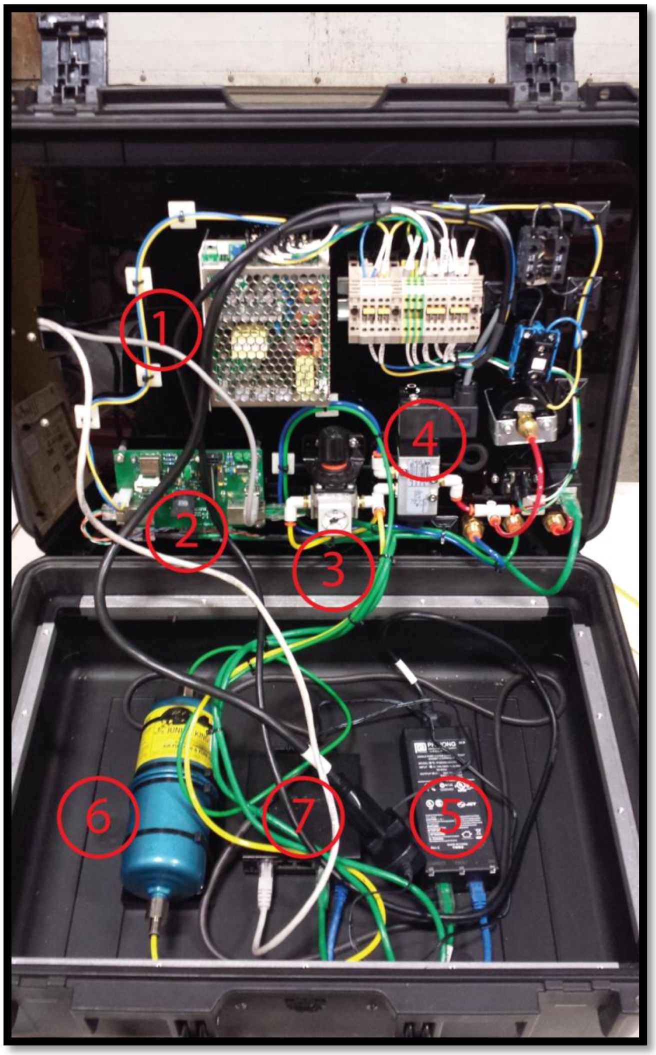

Figure 20 - OCS internals

Internal components are called out in Figure 20, these are:

1. 48VDC Supply
   a. 48VDC Supply for robot PoE
2. PoE Injector PCB
   a. PCB to inject 48VDC onto Ethernet lines for robot power.
3. Pressure regulator

    a. Takes incoming air and regulates down to 100PSI
4. Pneumatic valve interlock
5. Camera PoE injector
    a. Separate PoE injector for camera power
6. Inline air filter
7. Ethernet switch

C. Software

Figure 21 - User interface

Robot software is divided into two distinct parts, the user interface and the local control at the robot. The interface is responsible for providing a means of control and a convenient, non-cluttered display of all robot information. The local control of the robot is responsible for control of the individual robot modules while also reading, parsing and sending data back to the host.

6. User Interface

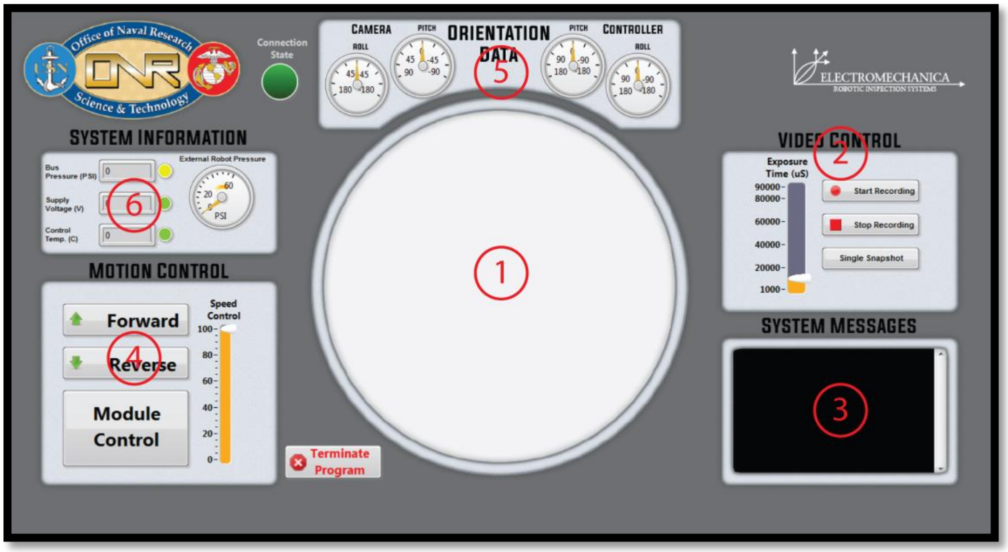

Figure 22 - User interface with label callouts

As previously mentioned, the user interface is responsible for providing the user a means of control, and for displaying all relevant robot information to the user. In addition, the user interface maintains a reliable TCP/IP connection to the robot for data transfer and control.

The interface can be seen in Figure 21 and Figure 22. Some of the features of the user interface are:

1. Video feed
    a. The video feed from the robot is displayed in the center of the window.
2. Video Control
    a. Exposure control varies the camera's light sensitivity. Allowing the user to tweak the image for the current lighting environment.
    b. Recording controls allow the user to record video of the inspection for later use.
    c. Single Snapshot allows the user to take a snapshot picture of the current video image.
3. System Messages
    a. Provides the user with relevant information pertaining to the robots operation.
4. Motion Control
    a. Command the robot to move forward or reverse.
    b. Speed control allows the user to slow the robot down for detailed inspection.
    c. Module control opens a sub panel, which allows the user to control each robot module separately.
5. Orientation Data
    a. Provides the user with spatial data from the robot.
        i. Camera roll & pitch
        ii. Controller roll & pitch

6. System Information
    a. Provides the user with system information
        i. Bus Pressure
        ii. Ambient Pressure
        iii. Supply voltage
        iv. Controller housing temperature

Video Feed

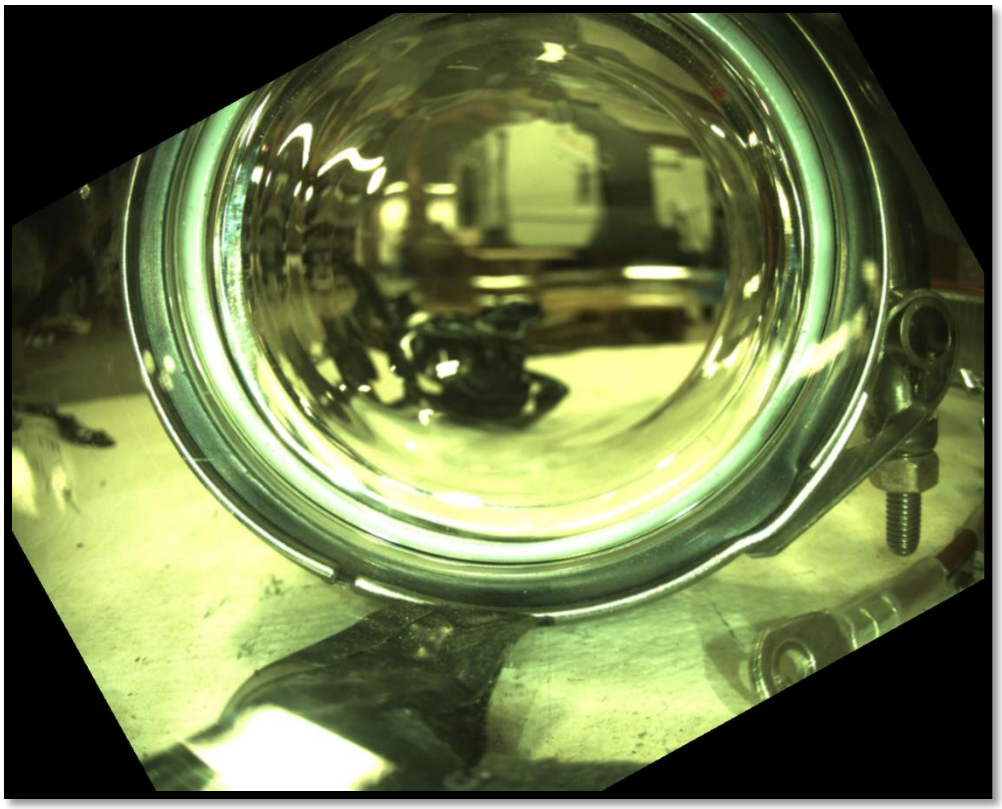

Figure 23 - Camera video feed

Internal pipe inspection presents a unique challenge from an imaging perspective. Unlike most camera applications, internal pipe images do not have a position reference for orientation. This piece of information is critical as it lets the operator know where the defect is located within the pipes circumference. Figure 24 shows an example. Without a known gravity reference, there is no position orientation.

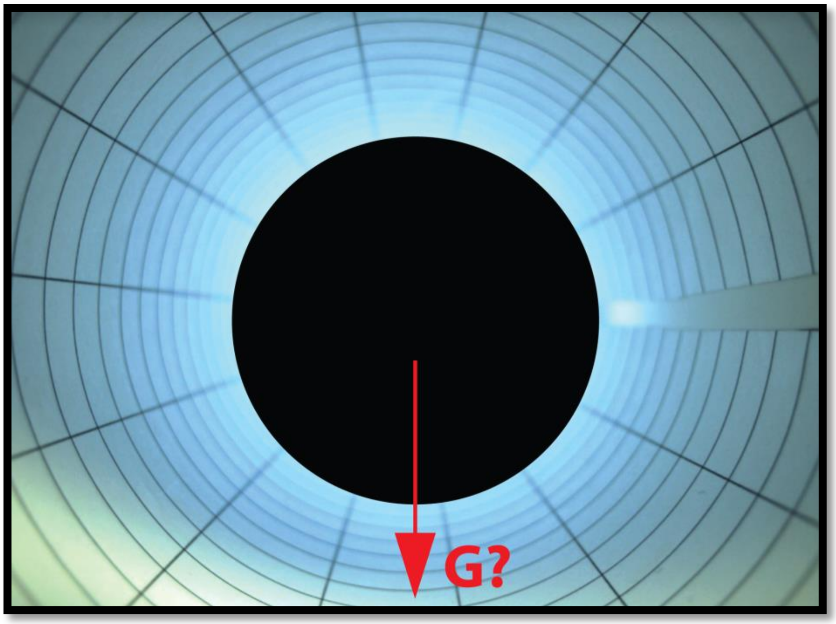

Figure 24 - Internal picture with unknown gravity reference

The solution to this problem was to obtain the roll of the camera, and modify the image accordingly. This was accomplished by integrating a 9-DoF IMU into the camera housing as previously mentioned. The roll value from this IMU was then used to roll the camera image in the opposite direction, allowing for the image to always be gravity referenced when in the horizontal plane. Unfortunately, this approach does not work in the vertical plane. It is anticipated that future work will integrate some type of dead reckoning which will allow for the system to know its orientation in all positions. See Figure 25 for a simple flow chart.

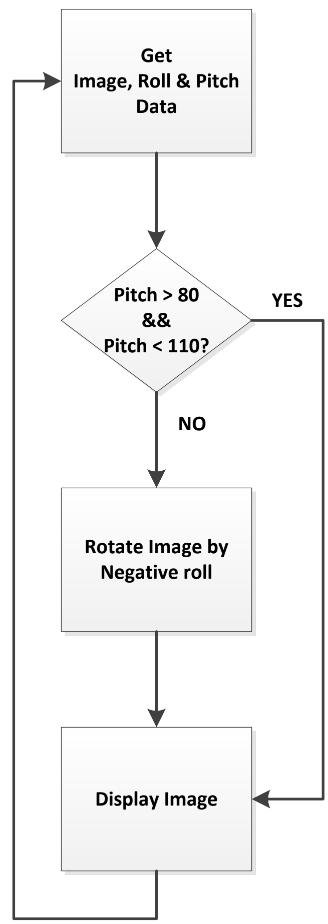

Figure 25 - Video rotation flow chart

7. Robot Local Control

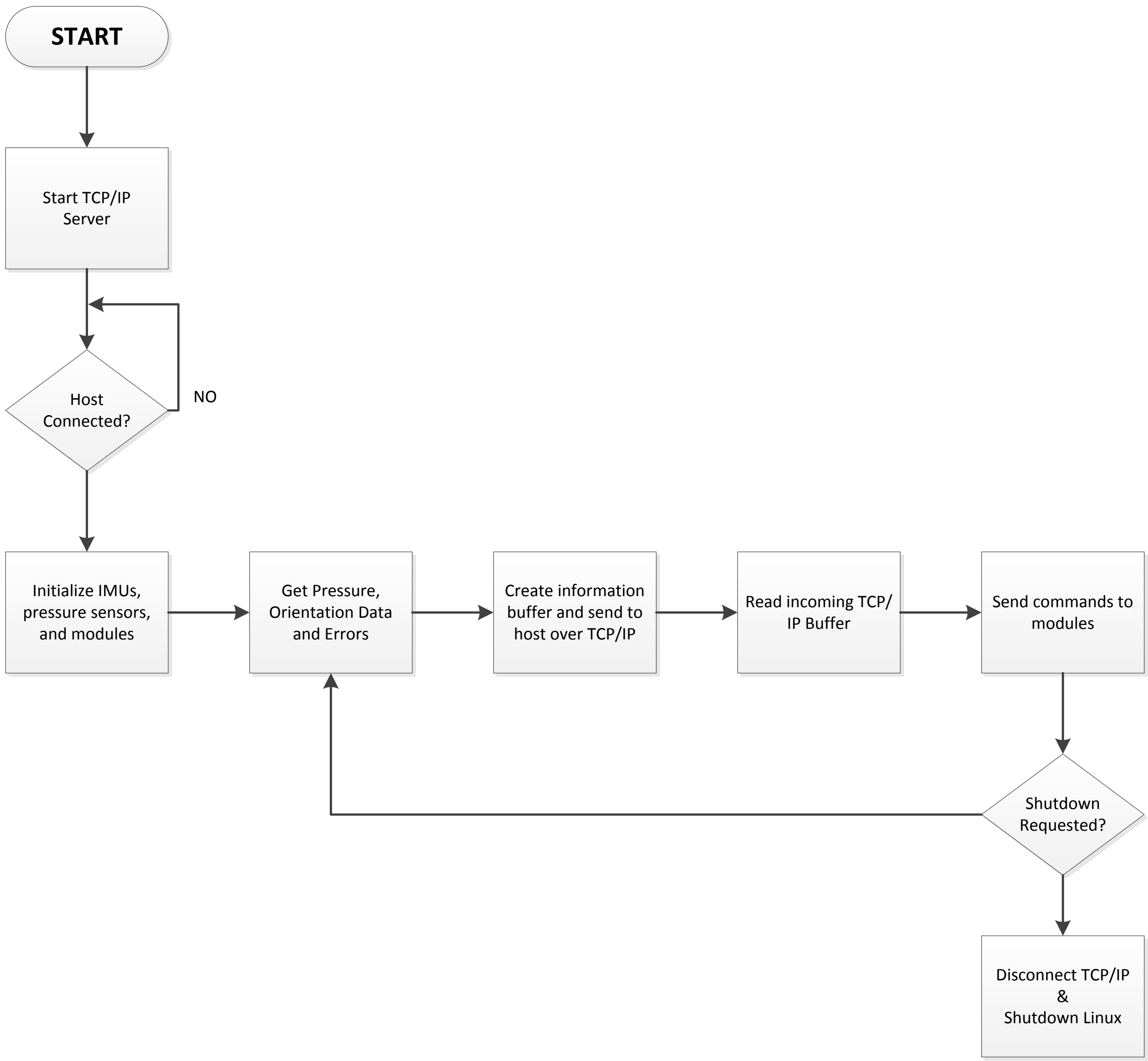

Figure 26 - Local control program flow chart

Local robot control is accomplished by an embedded Linux computer integrated into the robot as mentioned previously. Control is handled by a C program with state machine architecture. A simplified flow chart can be seen in Figure 26.

Module control and feedback is controlled directly by the local controller. If the master sends a command (forward/reverse) the system continuously runs the state machine required until the master sends a

different command. This method was chosen in order to negate the effects of latency or lost packets in the TCP/IP connection which could possibly degrade system performance.

The program also handles initialization and reading of the various sensors located on the robot. On initial boot, IMU settings are programmed via I2C. In addition, pressure sensor coefficients are read from the pressure sensors and stored in memory for pressure computation. After initialization the program repeatedly loops and reads IMU data and pressure data from each sensor. Data read over I2C is then processed and sent to the user interface via the TCP/IP connection.

D. Mechanical

8. Gripper

A new gripper was developed to utilize a COTs inflatable pneumatic seal and miniature pneumatic valves. It is comprised of a 5 part assembly machined from 6061-T6 Aluminum alloy

1. Rear gripper cone
2. Manifold cap
3. Seal core
4. Seal core cap
5. Nose cone

The rear cap houses the COTs mini valves and also has a built in manifold on the inside to divert the air between valves and delivering air further down the assembly. It also receives PoE cable through a bore offset from the center which makes connection to the circuitry inside, see Figure 27and Figure 28.

Figure 27 - Rear cone top view

Figure 28 - Rear cone bottom view

The manifold cap seals the air passageways on the rear cone using a custom gasket that sits in a machined pocket which creates a face seal between the gasket cap and the rear gripper cone, see Figure 29. The manifold than transfers air to the inflatable seal and also further down the assembly using a built in O-ring tube connector, see Figure 30.

Figure 29 – Air manifold cap top view

Figure 30 - Air manifold cap bottom view

The seal core is where the inflatable seal mounts to and resides at the center of the assembly. The inflatable seal slides onto the seal core's shaft and utilizes an O-ring tube connector for air it air supply, see Figure 31. It also offers a gasket pockets for sealing the gripper assembly's internals which will be further developed in the near future, see Figure 32.

Figure 31 - Seal core bottom view

Figure 32 - Seal core top view

The seal core cap contains the inflatable seal on the seal core and continues to transfer air to the pressure sensor which seats itself on the top face of the seal cap, see Figure 33 and also continues air through the assembly. It also includes a gasket pocket for sealing the gripper assembly's internals which will be further developed in the near future. The seal core cap utilizes two male and female O-ring tube connectors for making air connection between the seal core and the seal core cap, see Figure 33 and Figure 34.

Figure 33 - Inflatable seal cap top view

Figure 34 - Inflatable seal cap bottom view

The nose cone sits at the front of the gripper assembly and receives air from the seal core cap and diverts it forward to the remaining limbs of the robot. It also receives the PoE cable through the opening in the center of the cone, see Figure 35 and Figure 36.

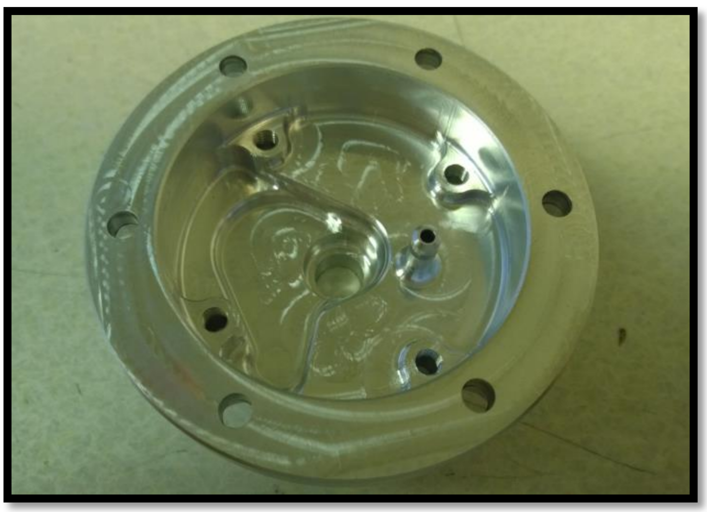

Figure 35 - Nose cone bottom view

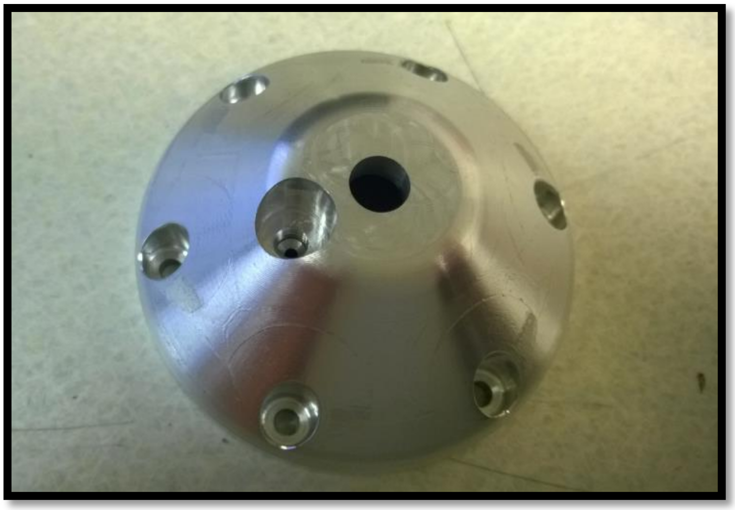

Figure 36 - Nose cone top view

The gripper assembly also contains the electronic controls which transfer Ethernet to the front of the robot and also commands the valves to operate in their respective sequences within the assembly. The gripper receives a bus air pressure of 100psi which is higher than the COTs seal can handle. However, the electronics within the assembly have a built in pressure sensor which safeguards the inflatable seals from failing due to over pressurizing them, see Figures below.

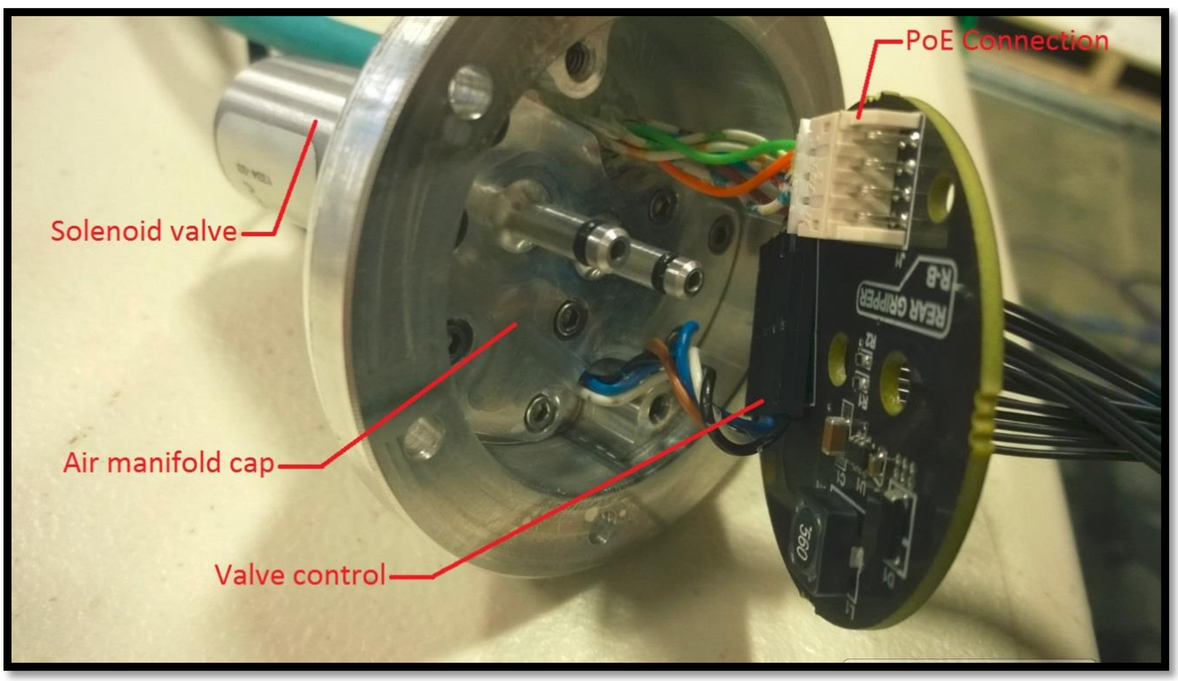

Figure 37 - Rear gripper cap dissection view

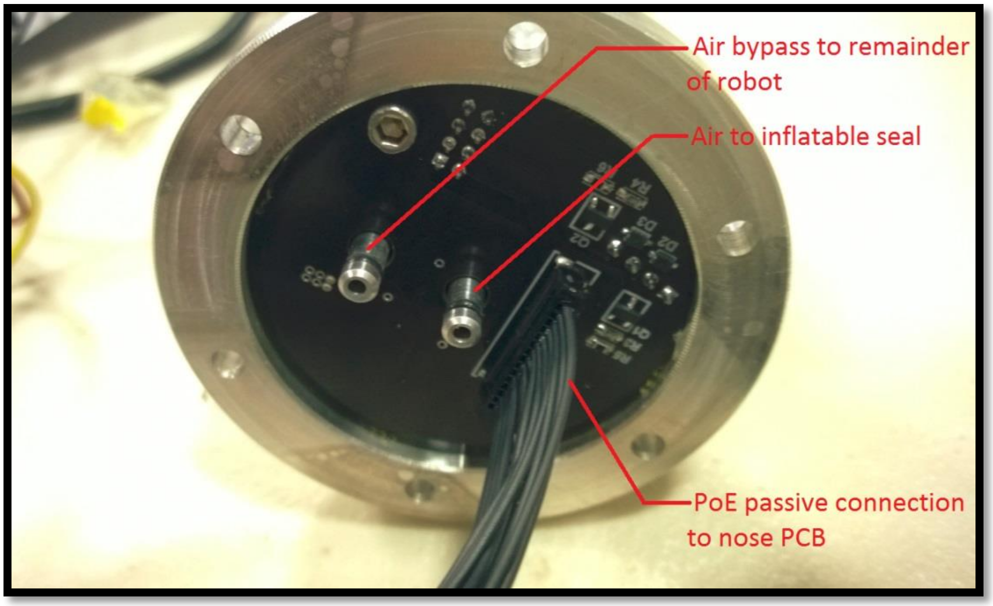

Figure 38 - Rear gripper cap assembled view

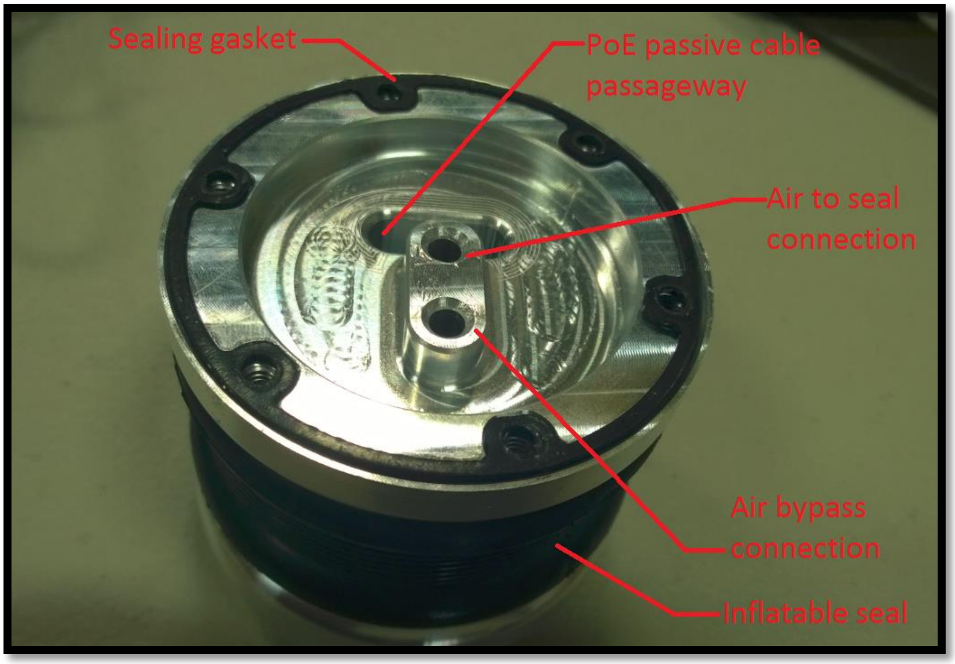

Figure 39 - Inflatable seal assembly rear view

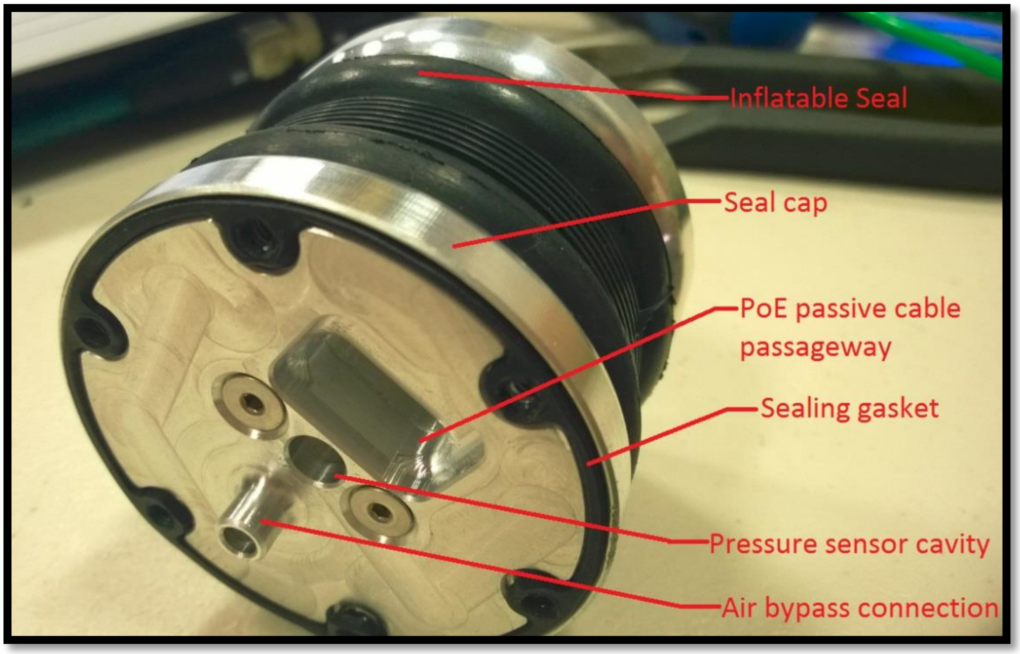

Figure 40 - Inflatable assembly front view

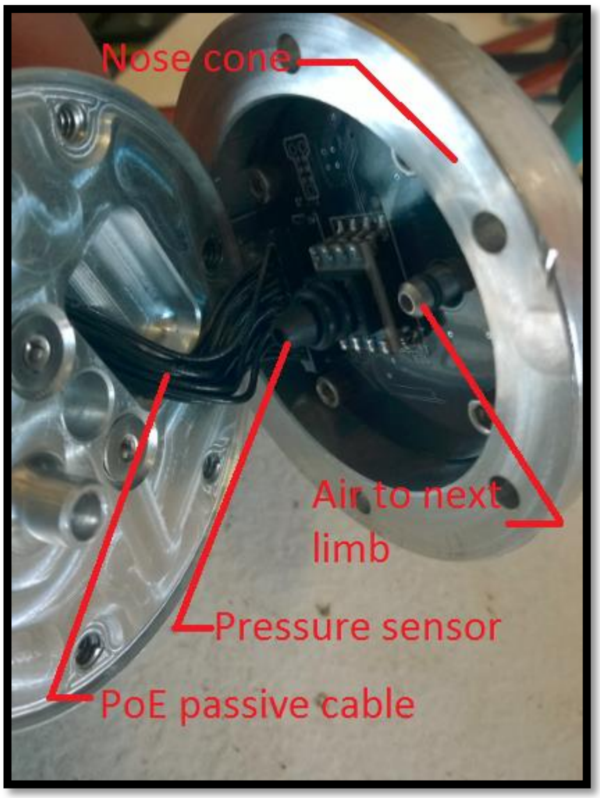

Figure 41 - Nose cone assembly

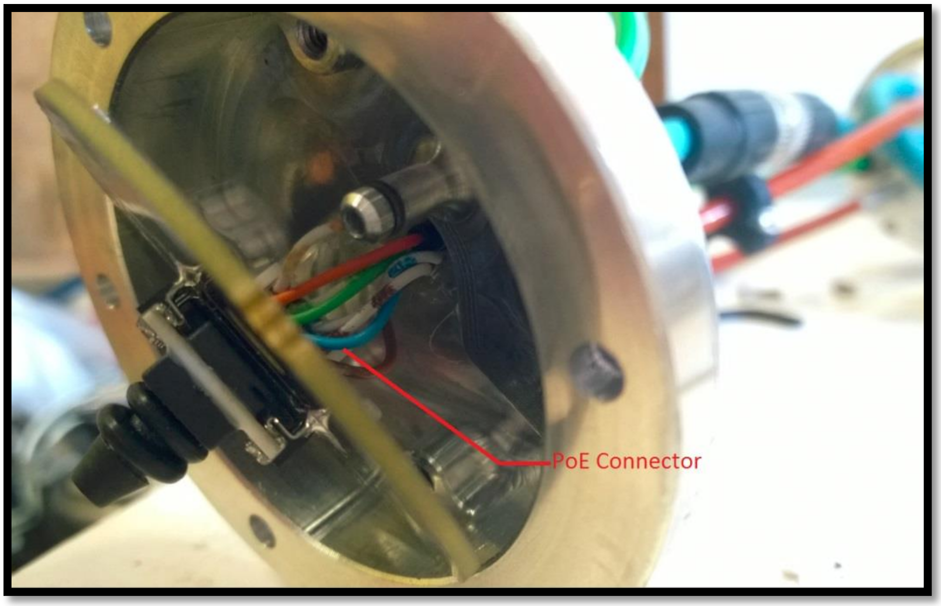

Figure 42 - Nose cone assembly PoE connector

Figure 43 - Assembled gripper

9. Flexible pneumatic cylinder

The flexible pneumatic cylinder is the core component of the robot. It is the robots drivetrain, allowing the robot to move forward and reverse within a plumbing network. It can be bent past 90° and still operate. This allows the robot to travel through a nonlinear sections of a plumbing network. The flexible pneumatic cylinder operates at 100 psi and utilizes two COTs mini pneumatic valves. It is comprised of a main assembly and a sub assembly.

The main assembly is comprised of 6 parts machined out of 6061-T6 Aluminum alloy

1. Cylinder rear cover
2. Cylinder rear base
3. Tube clamp
4. Cable clamp
5. Cylinder front base
6. Nose seal

The cylinder rear cover receives and sends the PoE cables to and from the control board located at the rear of the robot installed within the cylinder rear base. The cylinder rear cover also provides air to the assembly using an air fitting assembled on the cap. The rear cap also provides an anchor point for the linkage between the flexible pneumatic cylinder and the rear gripper, see Figure 44.

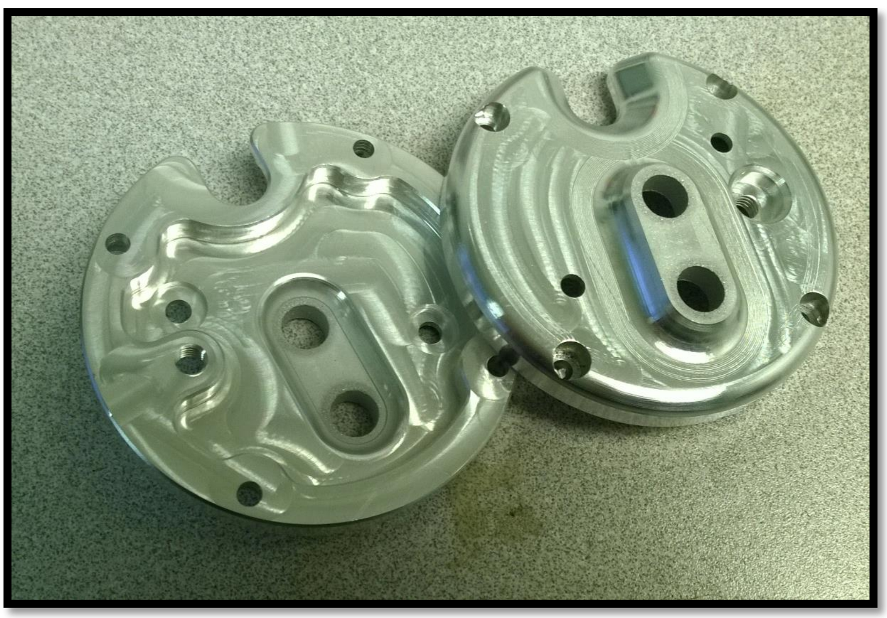

Figure 44 - Rear caps

The cylinder rear base is where the control board resides which also receives and delivers the PoE connection further down the assembly. The board controls the COTs mini pneumatic valves that allow the assembly to extend and retract. It communicates with the valves using a sealed 4 pin connector which threads to the top of the rear base and makes connection the controller board inside. The rear base has a built in manifold which diverts the incoming air to the mini valve, which drives the piston assembly

forward, and also out towards the front of the robot. It also has a cable strain relief feature built in to the side of the base. The rear base is also equipped with a snout to retain the flexible polyurethane Tygothane hose, which acts as both the cylinder wall for the piston and is also the main structural member of the flexible pneumatic cylinder assembly. The snout provides a 2° taper with an undercut on the snout. When the tube clamp, which also has a 2° taper, mates with the rear base's snout it cold flows the polyurethane into the undercut creating an anchor point for the tubing while also creating an air tight seal, see Figure 45and Figure 46.

Figure 45 - Rear cylinder base bottom view

Figure 46 - Rear cylinder base top view

The tube clamp is the retaining ring which seals and anchors the polyurethane tygothane tubing to the front and rear cylinder bases by method of taper locking the tube to the base's snouts. It is pressed on and then fastened to the bases utilizing four fasteners, see Figure 47 and Figure 48.

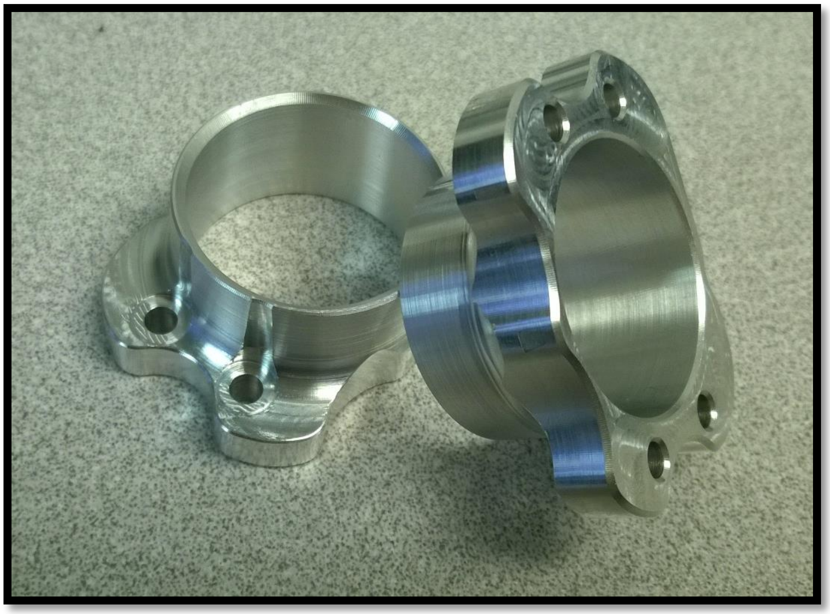

Figure 47 - Tube clamps

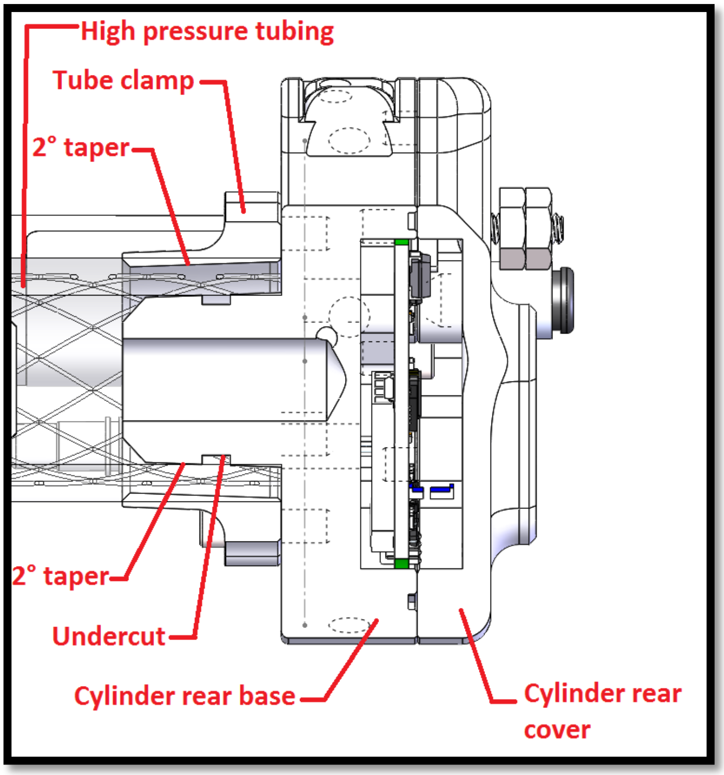

Figure 48 - Tube taper lock diagram

The cable clamp acts as an anchor point/strain relief for the PoE cable that runs towards the front of the robot, see Figure 49 and Figure 50.

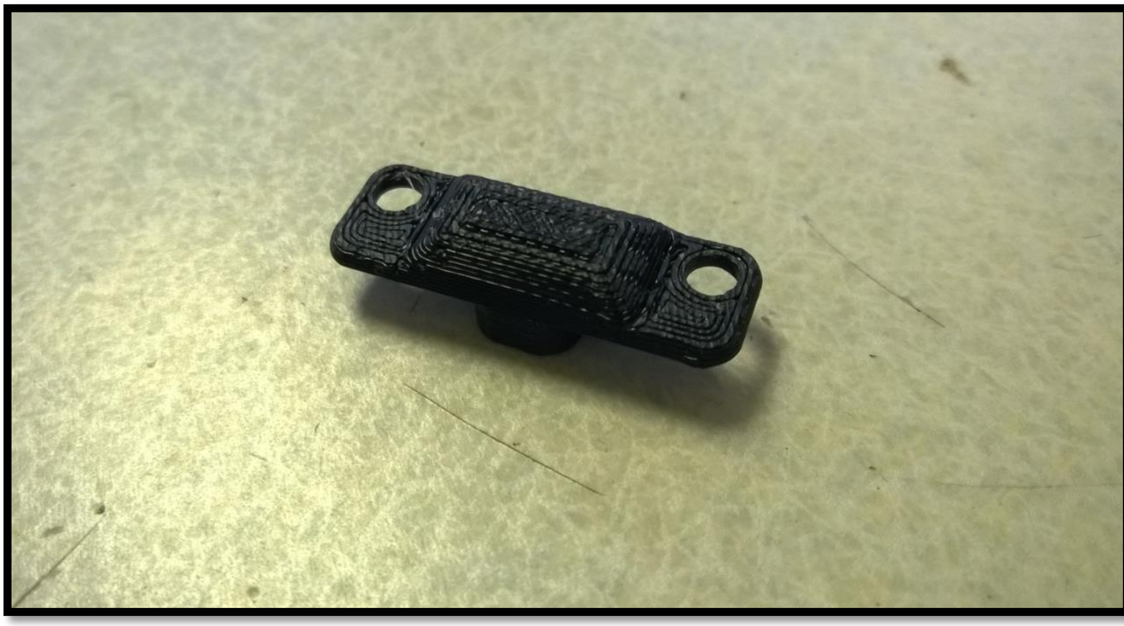

Figure 49 - Cable clamp

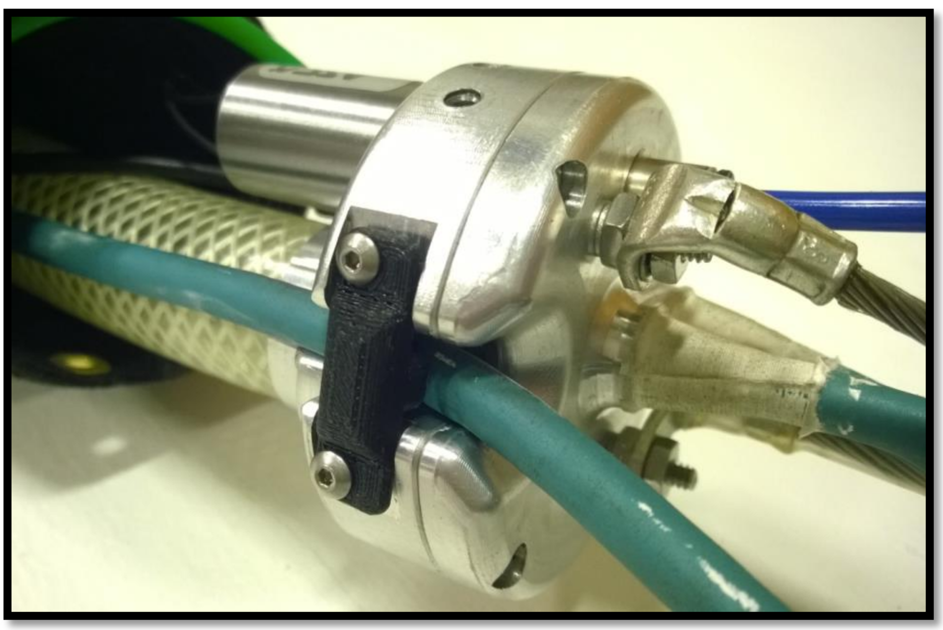

Figure 50 - Cable clamp installed

The cylinder front base is similar to the rear base aside from not having any enclosed electronics. It has a 2° tapered snout where the polyurethane tygothane tubing slides on to and which then receives the tube clamp locking it in place. The snout on the front base has a sealed bore which allows the piston rod to travel through allowing the piston assembly to move backwards/forwards while maintaining pressure. The

front base also has a built in manifold diverting incoming air to the mini pneumatic valve which drives the piston assembly backwards while also sending the air out towards the front of the robot, see Figure 51.

Figure 51 - Front tube cone

The nose seal provides the remainder of the sealing bore for the piston rod and also seals the cylinder front base both keeping air in and contaminants out. It also has a very rounded shape which allows to move smoothly in the pipe with very low risk of getting caught any defects or transitions within the pipe. The nose also has a rounded bore to allow the piston rod to bend and operate smoothly without getting caught on any sharp edges which could create chaffing on the rod which would result in a sealing failure, see Figure 52.

Figure 52 - Nose seal

Once fully assembled the flexible pneumatic cylinder has very abrupt edges which would increase the probability of it anchoring itself somewhere inside the piping system. A ballistic sleeve is fit over the length of the flexible pneumatic piston which protects components, allows for smoother transitioning, while still allowing the tube to bend and flex during operation, see Figure 53and Figure 54.

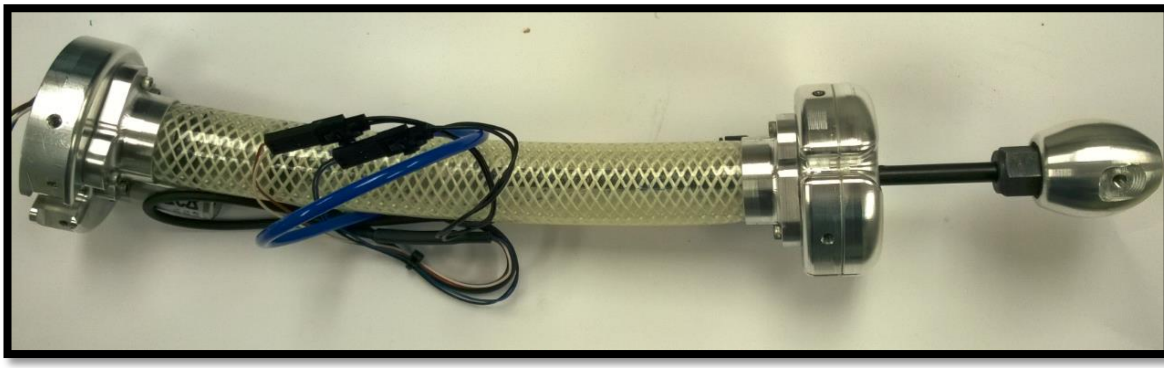

Figure 53 - Flexible pneumatic cylinder assembly

Figure 54 - Flexible pneumatic cylinder with sleeve

10. Piston assembly

The piston assembly is located within the polyurethane Tygothane tubing and consists of 6 unique parts.

1. Floating piston ring cap
2. Floating piston ring
3. Piston rod
4. Piston
5. Crimp tube
6. Rod connector

The floating piston ring and piston ring cap are adhered to each other by the piston which is a molded flexible adhesive which allows the piston rings to float independently from one another, see Figure 55.

Figure 55 - Piston assembly

The piston rings are the components which retain the quad core lip seals to the assembly. The piston assembly contains four of these quad core lip seals, two on each ring opposing one another. The lip seals are made of a quad ring loaded flexible polyurethane which expand, much like an umbrella, when air hits the front face of the seal. This forces the outer lip to conform against the cylinder wall and maintain a constants seal. This is an important feature due to the nature of the cylinder wall being a flexible tube the shape of the cylinder wall is constantly changing. The quad seal energizes lips further ensuring uniform positive lip contact with the cylinder wall at low pressures, see Figure 56.

Figure 56 - Quad core lip seal

At the core of the piston is a flexible stainless cable which is the backbone of the piston assembly. It allows for the piston and piston rings to flex independent of one another. At the core of the piston there's a stainless ferrule crimped onto the cable acting as a failsafe. In the event the piston core fails the ferrule catches onto the piston ring preventing the piston rod from projecting out of the flexible pneumatic cylinder assembly, see Figure 57.

At the nose of the piston assembly the stainless cable protrudes outward at a specified length. This segment of cable relieves the piston of side loading from the piston rod which causes sealing failures, see Figure 58.

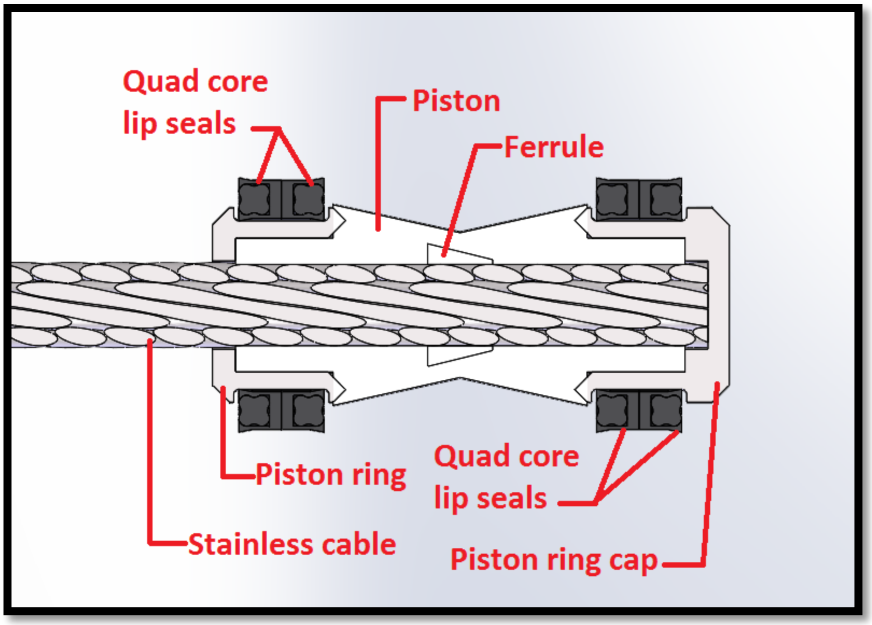

Figure 57 - Piston assembly diagram

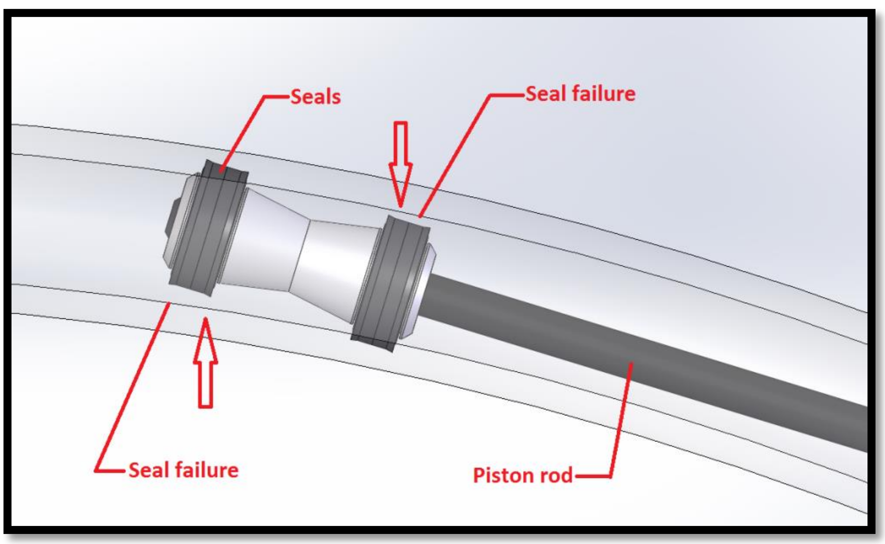

Figure 58 - Seal failure

The stainless cable is then attached to the piston rod using the crimp tube which is an aluminum crimp ferrule. The ferrule allows for the piston rod, which is made of Delrin, to cold flow into the ferule providing a high strength attachment method to anchor it to the stainless cable, see Figure 59 and Figure 60.

Figure 59 - Floating piston assembly with seals assembled

Figure 60 - Floating piston assembly

The rod connector attaches to the end of the piston rod, it is the attachment point for the linkages coming from the gripper assembly ahead. It uses a compression fitting with a stainless ferrule. Once crimped on the Delrin piston rod cold flows around the ferrule and locks it in place, see Figure 61.

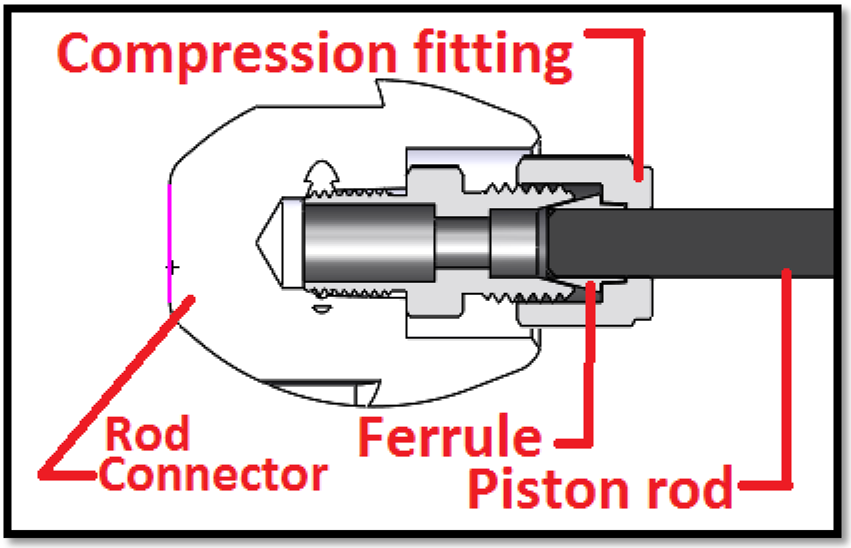

Figure 61 - Rod connector attachment diagram

11. Camera housing

The camera housing sits at the front of the robot and plays two roles. The first being a sealed capsule that houses the HD camera, lighting, and electronics, the second being that it acts as a guide for the remainder of the robot, specifically the front most gripper. It retains the front gripper as close to the centerline of the

pipe as possible. Without this guide the gripper would be at very odd angles when approaching a corner which would drastically reduce the seals effective surface area in contact with the pipe wall. This leads to a poor gripping surface area due to the robot being totally nonconcentric to the pipe geometry.

The camera housing consists of three fabricated components.

1. Front camera shell
2. Rear camera shell
3. Spring finger

The front camera shell will hold the lighting for the camera housing and allow the camera to mount to the nose of the cone to totally captivate the camera inside of the shell. Acrylic windows will protect the electronics and camera lenses. When fully assembled the spring fingers attach to the nose of the housing creating a smooth sloped surface aiding in the housings ability to enter irregular transitions with ease within the pipe, see Figure 62.

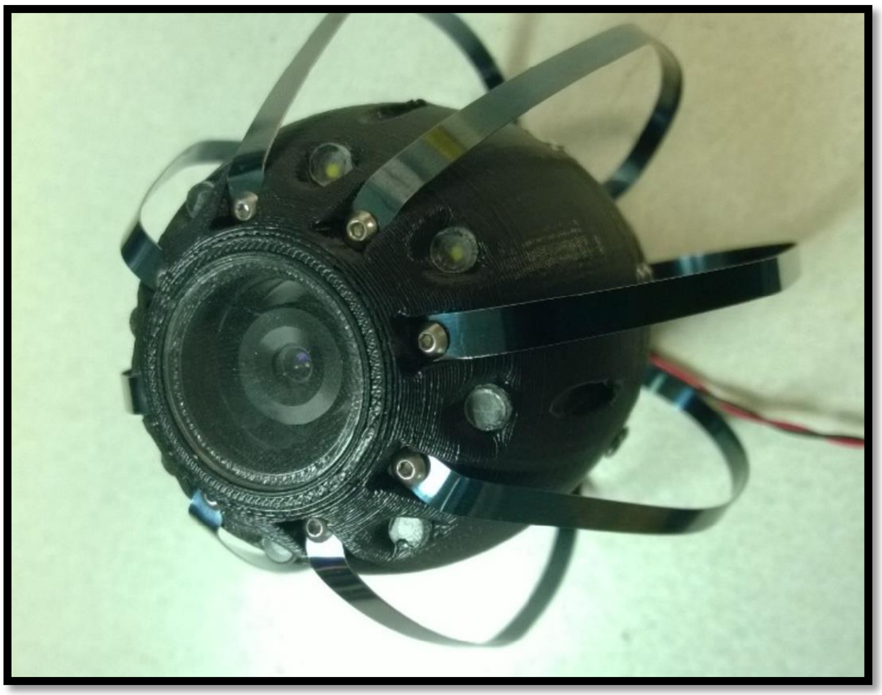

Figure 62 - Front view showing camera and lighting

The rear camera shell houses the electronics for driving the LED circuit and also sends and receives streaming video data via the PoE connector that is installed through the bottom of the housing. The rear camera shell also has attachment points for the linkages to fasten themselves onto, see Figure 63 and Figure 64.

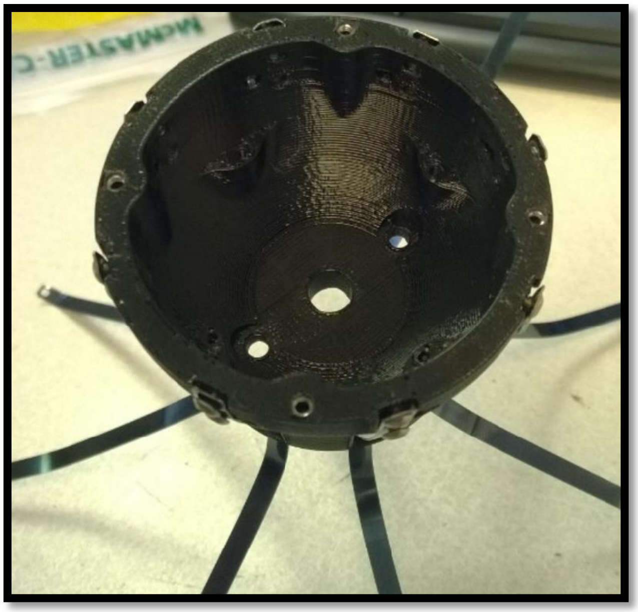

Figure 63 - Rear guide cone shell

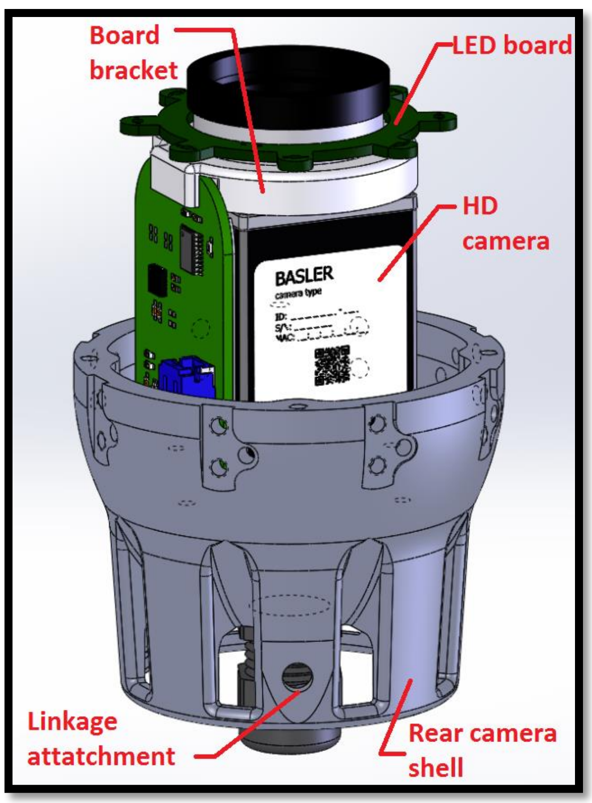

Figure 64 - Camera housing assembly diagram

The spring fingers act as a centering mechanism for the camera housing. The spring force of each finger pushes the camera housing towards the center of the pipe maintaining a concentric viewpoint for the operator. Without them the camera housing would flop and drag across the pipe floor limiting the cameras viewpoint and considerably handicapping thorough inspection. Once fully assembled the camera housing is a core component of the robot which provides both vision for the operator and guidance for the robotic limbs behind it, see Figure 65.

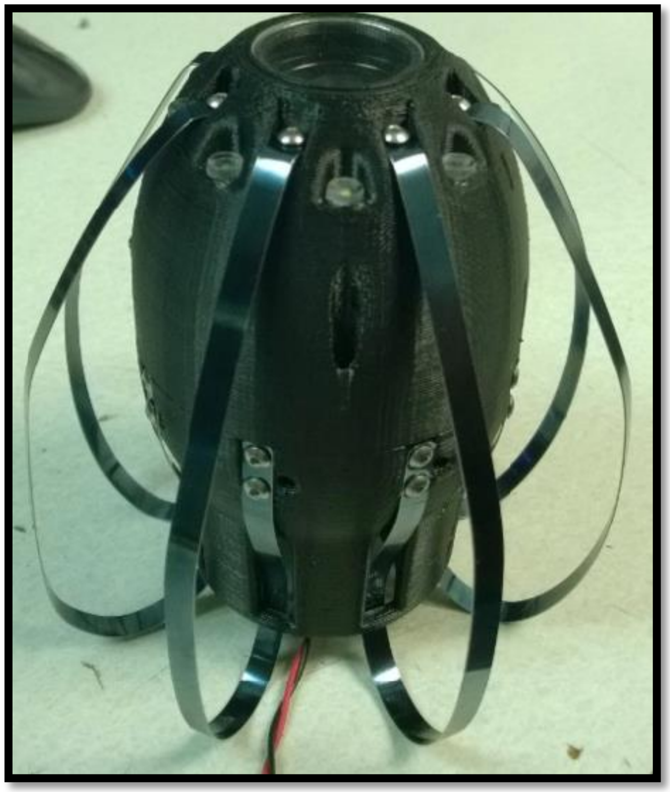

Figure 65 - Guide cone fully assembled

12. Linkages

The linkage system is comprised of two core components.

1. Stainless cable
2. Ring terminal

The stainless cable provides a flexible structural linkage between robotic limbs. It is rigid enough to push the robot forward yet flexible enough to allow the robot to conform to the bends of the piping network. On either end of the cable a ring terminal is attached which allows the cable to be fastened to each end of the robotic limbs. The crimp lug is filled with epoxy followed by the cable being inserted into the terminal. Finally a #8 crimp using dies is applied to the bottom of the ring terminal. This allows for a pocket of epoxy to cure inside the ring terminal. This method of attachment creates an anchoring effect drastically increasing the terminal's holding force, see Figure 66.

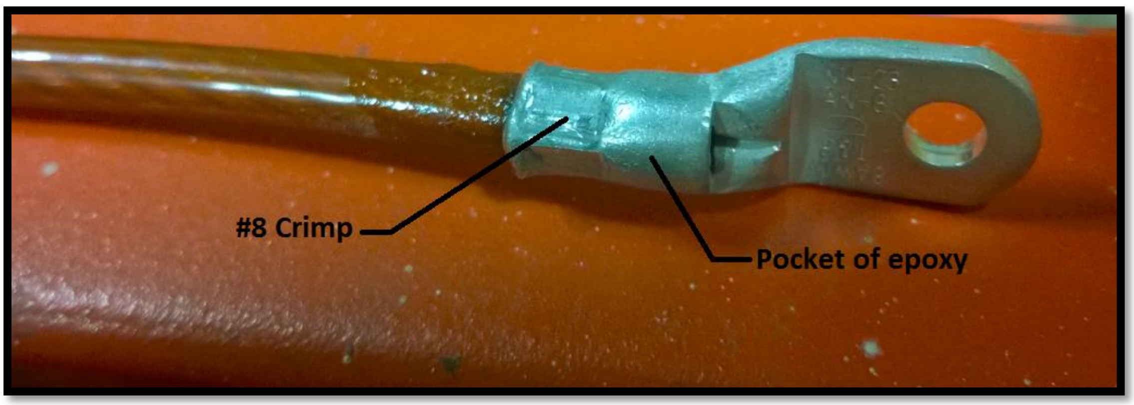

Figure 66 – Linkage assembly

Features are machined into ends of the robotic limbs to both fasten the linkage down and prevent the fasteners from coming loose minimizing the ring terminals rotation inside the pocket, see Figure 67, Figure 68 and Figure 69.

Figure 67 - Gripper cap machined under cuts

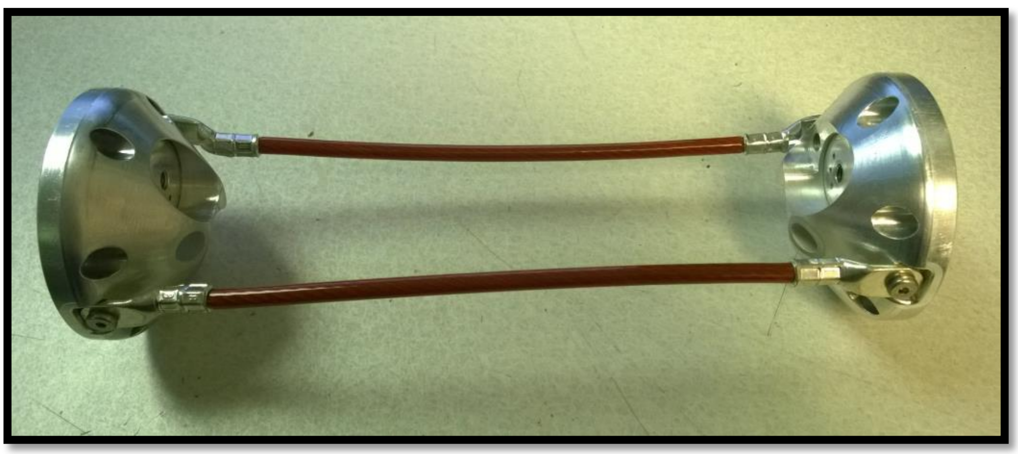

Figure 68 - Linkage assembly between segments

Figure 69 - Linkage fastened to gripper cap

13. Controller pod

The controller pod sits at the aft of the robot and houses all of the robots main circuitry. The housing is comprised of two parts machined from 6061-T6 Aluminum alloy.

1. Housing core
2. Housing core cap

The housing core has two functions, one being the frame that holds all the crucial electronics such as the embedded computer and secondly it acts as a heat sink for some of the more critical components.

Figure 70 - Housing core

The housing core cap provides a method for attaching the linkage cables to the pod while also providing a cone shaped nose on the opposite end of the housing core to help prevent it getting caught on any irregularities within the pipe, see Figure 71.

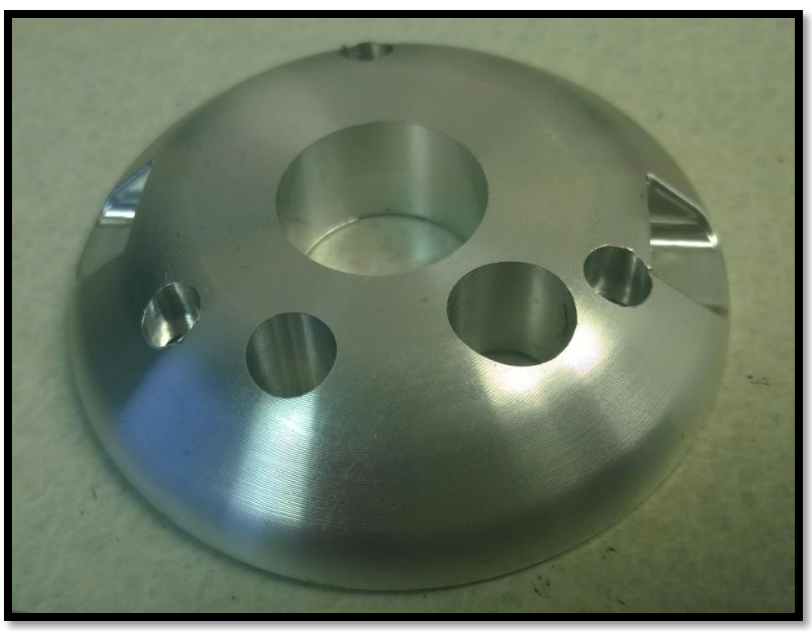

Figure 71 - Housing core cap

The housing has a protective cover made from acrylic tubing, the acrylic acts as a sealed impact guard, see Figure 72.

Figure 72 - Acrylic shield installed

IV. Future Work

Additional design and testing is required to improve the present robot design with the goal of producing a robotic inspection tool suitable for deployment to the fleet

Future work to refine the design will include:

- Improve the flexible linear actuator design developed in Ph2
  - Improve the reliability of the piston seal
  - Modify the piston core design with emphasis on manufacturability
- Implement environmental sealing
  - Investigate different sealing materials and sealing methods.
  - Implement and validate environmental protection of all robot components with the goal of safe operation in wet or submerged environments
- Integrate and demonstrate inspection and remediation tools
  - Partner with 3^{rd} party vendors to integrate tools
  - Demonstrate the capability of the robot to deploy tools and payloads
- Investigate ability to map plumbing system while navigating through the systems
  - Develop different methods of creating a 2D/3D map of the route taken
  - Develop method of displaying data to be easily read and interpreted
  - Fuse sensor data from orientation sensors and other information streams such as video or inspection tool data
- Design a steering mechanism
  - Design and build a steering head mechanism to selectively and deterministically negotiate different paths within the plumbing network
  - Demonstrate the ability to negotiate sharp bends, tee and wye fittings and other obstacles
- Design and implement robust software and hardware error handling
  - Watchdog timers to prevent I2C module hang ups
  - Error handling, prioritization and recovery

V. Conclusion

Electromechanica has designed and fabricated a fully functional and robust working prototype. Peristaltic motion inside the pipe was demonstrated. The prototype robot has the ability to navigate complex plumbing systems horizontally and vertically including bends. The flexible linear actuator was designed and it's unique capabilities demonstrated. Electromechanica, Inc. has applied for a provisional patent for the flexible linear actuator. Additional robot functions including a high definition camera, pressure sensors and orientation sensors were implemented in the prototype and demonstrated.

Future work is required to further refine the robot design and improve it's capabilities if the system is to be deployed for in-situ inspection of fleet piping.

VI. Financial

Month	Period	CLIN	Milestone Payment	Payment Total Cumulative	% Project Total Cumulative
1	JAN - 2014	0001	$ 42,000.00	$ 42,000.00	7.0%
2	FEB - 2014	0002	$ 42,000.00	$ 84,000.00	14.0%
3	MAR - 2014	0003	$ 42,000.00	$ 126,000.00	21.1%
4	APR - 2014	0004	$ 42,000.00	$ 168,000.00	28.1%
5	MAY - 2014	0005	$ 42,000.00	$ 210,000.00	35.1%
6	JUN - 2014	0006	$ 42,000.00	$ 252,000.00	42.1%
7	JUL - 2014	0007	$ 42,000.00	$ 294,000.00	49.2%
8	AUG - 2014	0008	$ 42,000.00	$ 336,000.00	56.2%
9	SEP - 2014	0009	$ 42,000.00	$ 378,000.00	63.2%
10	OCT - 2014	0010	$ 42,000.00	$ 420,000.00	70.2%
11	NOV - 2014	0011	$ 42,000.00	$ 462,000.00	77.2%
12	DEC - 2014	0012	$ 77,089.00	$ 539,089.00	90.1%
	Subtotal		$ 539,089.00		
	Option	0013	$ 59,000.00		100%
	Total		$ 598,089.00		
	Note: The option (CLIN0013) was not funded				